NASA/CR—2008-215224

System Study

Technology Assessment and Prioritizing Update

General Electric Aircraft Engines
Cincinnati, Ohio

May 2008

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Prepared under Contract NAS3–01135, Work element 1.1, Task order 37

National Aeronautics and
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Preface

This final report summarizes the efforts of many participants, all of whom were instrumental in the successful completion of the Propulsion 21 systems study. They are:

GE Aviation

Paul Cooker	System Study Principal Investigator
Greg Steinmetz	Technical support and coordination
Steve Martens	Acoustic technologies
Bob Burgholz	Thermal management and advanced cooling
Ming Xie & Steve Mitchell	Smart containment system
Bill Myers	Intelligent combustor
Voytek Sak & Ron Maruscik	Engine deterioriation
Jorge Seda	Work element technical manager

NASA

Clayton Meyers

Michael Tong

1.0 Executive Summary

1.1 Task Objectives

The objective of this Work Element was to update the technology assessment (ranking) model to prioritize advanced technologies required to achieve the proposed Propulsion 21 Technology Program system goals for emissions, noise, safety, and reliability as a function of fuel burn, noise, and emissions (NOx) by building upon the work completed under the NASA RASER contract NAS3–01135, Task Order 23, Work Element 4.1 – System Study. In addition, selected technologies were combined to perform an engine–level trade study aimed at assessing their overall benefits to the system.

Four technologies, included in NAS3–01135 Task Order 37, were not included in the system study because they did not have a direct effect on engine fuel burn, noise or NOx emissions. These were: disk life meter, adaptive controls, bearing systems and fuel systems. In addition, advanced materials, although previously assessed under NASA program NAS3–98004 Task Order 14, were not part of this task's scope.

Key GE–Aviation (GEA) deliverables were the Technology Audit Database (TAD) and the Technology Impact Matrix (TIM) with benefits and debits for all proposed technologies. System–level impact was determined by combining beneficial technologies with minimum conflict among various system figures of merit to assess their overall benefit to the system. The shortfalls and issues with modeling the proposed technologies were identified and recommendations for future work proposed.

1.2 Study Results

The final TIM for the 2015 Ultra Efficient Engine Technology – Quiet Aircraft Technology (UEET–QAT) engine technologies is shown in Table 1 and the template for all technologies used to genetate the TAD is given in Table 2. Figures 1 through 3 show the impact of each proposed technology on the 2015 UEET–QAT engine in terms of fuel burn, noise, and NOx emissions respectively. The impact of high–pressure turbine (HPT) clearance control on deteriorated engines is also shown in Figures 1–3. On the left side of the figures, the technology list is shown, consistent with Table 1. The technology numbering (simplified as "T" followed by a number) listed in Table 1 will be referred throughout the report unless otherwise indicated. Throughout this study, fuel burn refers to the fuel burn at a 5600 nautical mile (nm) mission.

The top six fuel burn technology rankings for a new engine were:

1. T18 (cooled cooling air used for active clearance control (ACC))
2. T19 (low–pressure turbine (LPT) nozzle cooling air used for ACC)
3. T7 (intelligent HPT rotor cooled cooling air system)
4. T11 (advanced HPT stage 1 blade)
5. T20 (mechanical actuators)
6. T15 (HPT endwall contouring)

For deteriorated engine cases, T18–20D and their fuel burn impact is shown in Figure 1. T18 and T19 are two different methods used to achieve turbine clearance control and are based on elastic

Table 1. Technology Impact Matrix for the Proposed 2015 UEET-QAT Balanced Noise EROC Engine

		Δ Prop. System Wt (lbs)	Δ Prop. System Wt (lbs) Cycled	Δ HPT - Stg1 Ch. Wcl	Δ HPT Stg2 Ch. Wcl	Δ HPT Effic. ED41	Δ Fuel Burn	Δ MTOGW Range, nm	Δ Cum. Margin, dB
Acoustics									
T1	**- Synthetic Jet Fluidic Injection**								
T2	**- Shape memory alloy chevron nozzle**								
T3	**- Active Liners**								
T4	**- Long Duct Chevron Mixer**								
T5	**- Plasma Actuators**								
T6	**- Vortex Stabilizing Jet**								
Thermal Management and Advanced Cooling									
T7	**- Intelligent HPT rotor cooled cooling air system**								
T8	**- HPT stage 1 rotor cooling flow control**								
T9	**- HPT stage 2 vane cooling flow control**								
T10	**- Fluidic flow control**								
T11	**- Advanced HPT stage 1 blade**								
T12	**- Cored HPT shroud**								
T13	**- 3D HPT cooling optimization**								
T14	**- High-temperature sensors**								
T15	**- HPT flowpath endwall contouring**								
Smart containment system									
T16	**Advanced Structure & Containment Fab, Advanced Nanofiber diagnostics**								
Intelligent combustor									
T17	**TAPS SAC Mixer, MOD 2+**								
HPT clearance control (EGT overshoot)									
T18	**- Cooled Cooling Air for ACC**								
T19	**- LPT nozzle Cooling Air for ACC**								
T20	**- Mechanically actuated shrouds**								

GEAE: 49 deg C deteriorated engine

HPT clearance control (deteriorated engine)									
T18-20 D	**Deteriorated technologies T18 - T20 (.01 max)**								

Table 2. Technology Audit Database Template Sheet

Audit Sheet Focus	Information Desired	Result or answer	Additional Comments
0a	Date template filled out		
0b	Point of Contact Name		
0c	Point of Contact Email		
0d	Point of Contact Phone Number		
1	Technology Name		
2	What engine class or vehicle system is the primary application?		
3	Detailed Technology Description		
4	Current TRL		
5a	Description of technology's **positive** impacts to the system		
5b	3-point estimates of this technology's **positive** impacts to the engine/vehicle		
5c	What is your confidence in the projections (3-point estimates) of the **positive** impacts?		
5d	What is (are) the point(s) of reference of the **positive** impacts?		
5e	Desired direction of change for each **positive** metric		
6a	Description of technology's **negative** impacts to the system		
6b	3-point estimates of this technology's **negative** impacts to the engine/vehicle		
6c	What is your confidence in the projections (3-point estimates) of the **negative** impacts?		
6d	What is (are) the point(s) of reference of the **negative** impacts?		
6e	Desired direction of change for each **negative** metric		
7a	How are the **positive** and **negative** impacts of the technology quantified or measured?		
7b	Are you able to measure the impacts on a regular basis?		
8a	**Goal** for technology impact levels at TRL=6		
8b	**Minimum Success Criteria** for technology impact levels at TRL=6		
9a	Degree of Difficulty (R&D3) of reaching the TRL=6 goal values?		
9b	If applicable, what is the upper limit (physical limit) of the positive impact(s) of the technology?		
10a	*Current* percentage complete of technology		
10b	Total number of years in development		
11a	When will *TRL=2* be achieved from the current percentage complete		
11b	When will *TRL=3* be achieved from the current percentage complete		

Acoustics	
T1	**– Synthetic Jet Fluidic Injection**
T2	**– Shape memory alloy Fan chevron Nozzle**
T3	**– Active Liners**
T4	**– Long Duct Chevron Mixer**
T5	**– Plasma Actuator**
T6	**– Vortex Jet Stabilizer**
Thermal Management and Advanced Cooling	
T7	**– Intelligent HPT rotor cooled cooling air system**
T8	**– HPT stage 1 rotor cooling flow control**
T9	**– HPT stage 2 vane cooling flow control**
T10	**– Fluidic flow control**
T11	**– Advanced HPT stage 1 blade**
T12	**– Cored HPT shroud**
T13	**– 3D HPT cooling optimization**
T14	**– High-temperature sensors**
T15	**– HPT flowpath endwall contouring**
Smart containment system	
T16	**Advanced Structure & Containment Fab, Advanced Nanofiber diagnostics**
Intelligent combustor	
T17	**TAPS SAC Mixer, MOD +2**
HPT clearance control (EGT overshoot)	
T18	**– Cooled Cooling Air used for ACC**
T19	**– LPT nozzle Cooling Air used for ACC**
T20	**– Mechanical actuators**
T18-20 D	**Deteriorated technologies T18 - T20 (.01 max)**

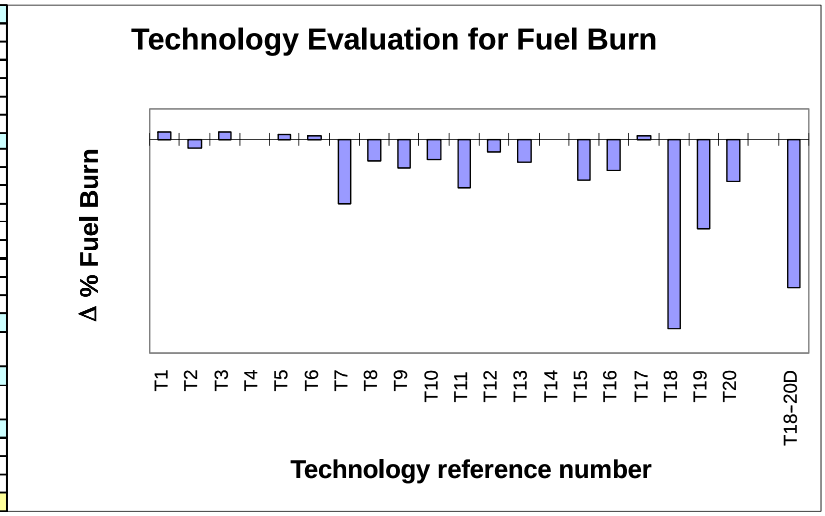

Figure 1. Technology Evaluation for Fuel Burn at 5600nm
Potential for -1.4% improvement from 2015 UEET-QAT baseline.

Acoustics	
T1	**– Synthetic Jet Fluidic Injection**
T2	**– Shape memory alloy Fan chevron Nozzle**
T3	**– Active Liners**
T4	**– Long Duct Chevron Mixer**
T5	**– Plasma Actuator**
T6	**– Vortex Jet Stabilizer**
Thermal Management and Advanced Cooling	
T7	**– Intelligent HPT rotor cooled cooling air system**
T8	**– HPT stage 1 rotor cooling flow control**
T9	**– HPT stage 2 vane cooling flow control**
T10	**– Fluidic flow control**
T11	**– Advanced HPT stage 1 blade**
T12	**– Cored HPT shroud**
T13	**– 3D HPT cooling optimization**
T14	**– High-temperature sensors**
T15	**– HPT flowpath endwall contouring**
Smart containment system	
T16	**Advanced Structure & Containment Fab, Advanced Nanofiber diagnostics**
Intelligent combustor	
T17	**TAPS SAC Mixer, MOD +2**
HPT clearance control (EGT overshoot)	
T18	**– Cooled Cooling Air used for ACC**
T19	**– LPT nozzle Cooling Air used for ACC**
T20	**– Mechanical actuators**
T18-20 D	**Deteriorated technologies T18 - T20 (.01 max)**

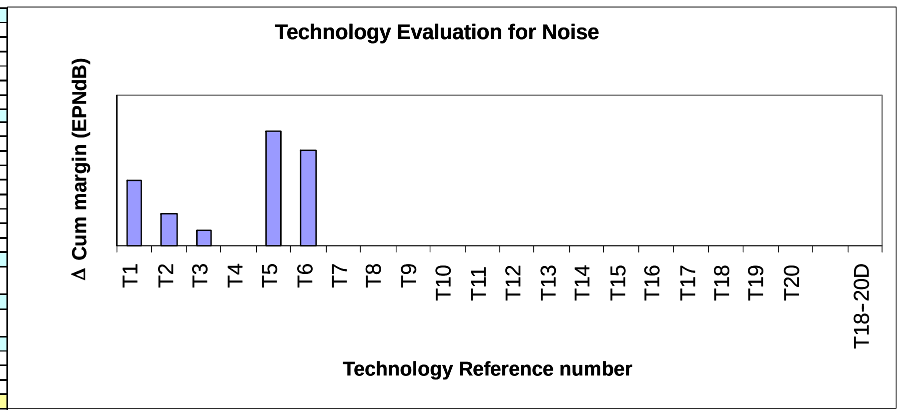

Figure 2. Technology Evaluation for Noise
Potential for +1.9 EPNdB Margin from 2015 UEET-QAT baseline

Acoustics	
T1	**– Synthetic Jet Fluidic Injection**
T2	**– Shape memory alloy Fan chevron Nozzle**
T3	**– Active Liners**
T4	**– Long Duct Chevron Mixer**
T5	**– Plasma Actuator**
T6	**– Vortex Jet Stabilizer**
Thermal Management and Advanced Cooling	
T7	**– Intelligent HPT rotor cooled cooling air system**
T8	**– HPT stage 1 rotor cooling flow control**
T9	**– HPT stage 2 vane cooling flow control**
T10	**– Fluidic flow control**
T11	**– Advanced HPT stage 1 blade**
T12	**– Cored HPT shroud**
T13	**– 3D HPT cooling optimization**
T14	**– High-temperature sensors**
T15	**– HPT flowpath endwall contouring**
Smart containment system	
T16	**Advanced Structure & Containment Fab, Advanced Nanofiber diagnostics**
Intelligent combustor	
T17	**TAPS SAC Mixer, MOD +2**
HPT clearance control (EGT overshoot)	
T18	**– Cooled Cooling Air used for ACC**
T19	**– LPT nozzle Cooling Air used for ACC**
T20	**– Mechanical actuators**
T18-20 D	**Deteriorated technologies T18 - T20 (.01 max)**

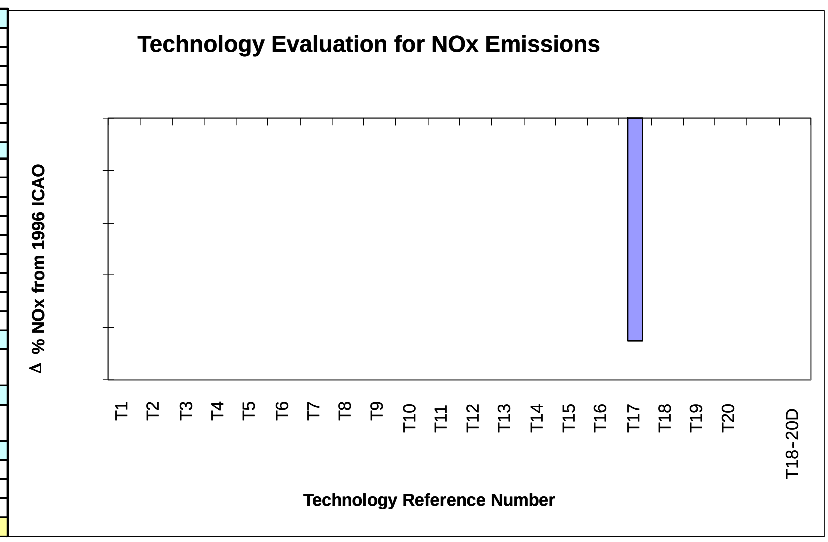

Figure 3. Technology Evaluation for LTO NOx
T17 NOx is 85% below 1996 ICAO limit.
50% NOx reduction from 2015 UEET-QAT baseline.

stretch and advanced thermal systems. T20 used more traditional mechanical actuators and the benefits were derived from NASA-provided rig testing information. T18 and T20 targeted to recover a reasonable amount in deteriorated HPT adiabatic efficiency. The difference was that T20 required more HPT chargeable cooling flow due to more leakage passages from its segmented hardware.

Among the acoustic technologies T5 (plasma actuators), T6 (vortex jet stabilizer), T1 (synthetic jet fluidic injection), and T2 (shape memory alloy fan chevron nozzle) had the most acoustic benefits. Considering the acoustic technologies, only T3 had a beneficial fuel burn advantage. T6, T2, and T3 were selected for the engine system because they provided the highest benefits while being compatible with each other as shown in Table 3. Among the emission technologies, T17 (GEA intelligent combustor) reduces NOx by 50% from the baseline 2015 UEET-QAT engine level, equivalent to 15% additional reduction from 1996 ICAO limit. In other words, the 2015 UEET-QAT baseline is 70% below 1996 ICAO limit while the Propulsion 21 baseline is 85% below 1996 ICAO limit.

Table 3. System-Level Engine Impact
Potential 1.89 EPNdB cum noise margin improvement, 1.34% fuel burn, and 50% NOx reduction from 2015 UEET-QAT engine/aircraft baseline

		Best Eng. System Impact - Fuel Burn Tech Only	Best Eng. System Impact - Noise Tech Only (dB)	Eng. System Impact - All Compatible Tech
Acoustics				
T1	**- Synthetic Jet Fluidic Injection**			
T2	**- Shape memory alloy chevron nozzle**		X	X
T3	**- Active Liners**		X	X
T4	**- Long Duct Chevron Mixer**			
T5	**- Plasma Actuators**			
T6	**- Vortex Stabilizing Jet**		X	X
Thermal Management and Advanced Cooling				
T7	**- Intelligent HPT rotor cooled cooling air system**			
T8	**- HPT stage 1 rotor cooling flow control**	X		X
T9	**- HPT stage 2 vane cooling flow control**	X		X
T10	**- Fluidic flow control**	X		X
T11	**- Advanced HPT stage 1 blade**	X		X
T12	**- Cored HPT shroud**	X		X
T13	**- 3D HPT cooling optimization**	X		X
T14	**- High-temperature sensors**			
T15	**- HPT flowpath endwall contouring**	X		X
Smart containment system				
T16	**Advanced Structure & Containment Fab, Advanced Nanofiber diagnostics**	X		X
Intelligent combustor				
T17	**TAPS SAC Mixer, MOD +2**	X		X
HPT clearance control (EGT overshoot)				
T18	**- Cooled Cooling Air for ACC**	X		X
T19	**- LPT nozzle Cooling Air for ACC**			
T20	**- Mechanically actuated shrouds**			
T18-20 D	**Deteriorated technologies T18 - T20 (.01 max)**			
	Total Engine System	**-1.35%**	**1.89**	**-1.34%**

The engine system level impact was estimated by selecting the most compatible technologies and including all their beneficial effects. The final system contains all the proposed technologies except for T1, T4, T5, T7, T14, T19 and T20. The engine system level impacts from combining all the technologies are shown in Table 3. With respect to the 2015 UEET–QAT baseline, fuel burn was reduced by 1.34%, noise (cumulative margin) improved by 1.89 EPNdB, and NOx emissions were reduced by 50%.

All the above technology evaluation results, except for T18–20D, were based on new engine designs. In modeling the benefits of the proposed technologies, the new engine was resized to obtain the maximum benefit while retaining the same cycle parameters as the 2015 UEET–QAT baseline. The 2015 UEET–QAT baseline engine was designed with an optimized cycle that minimizes fuel burn with balanced noise and Engine Related Operating Cost (EROC).

An exhaust gas temperature (EGT) trending algorithm was developed but cannot be viewed as a successor or substitute for the types of analysis that are currently performed by various commercial engine tracking and trending operations. The primary purpose of the exercise was to demonstrate how a credible engine EGT signature could be synthesized from the relatively sparse and “noisy” sets of data available from turbofans in airline service, and how the data could be used to characterize engine deterioration in a more simplified manner. This data was supplied to university specalists who were developing engine deterioration models

1.3 Conclusions

For the Intelligent Engine System (Propulsion 21) study, each technology was evaluated to determine the impact to fuel burn, acoustics, and NOx emissions. The optimum combination of technologies and their overall benefits to the system were also evaluated, resulting in noise improvement potential of 1.89 EPNdB cumulative margin, –1.34% fuel burn, and 50% NOx reduction from the 2015 2015 UEET–QAT baseline. All the technology evaluations, except T18–20D, were based on new engines, where the engine was resized to obtain the maximum system benefit while maintaining the same cycle parameters as the 2015 UEET–QAT baseline. The impact of turbine clearance control on deteriorated engines, T18–20D, was also evaluated.

Recommendations for future system study work include, but were not limited to, validation of a university–developed engine deterioration model and customer value analysis as figures of merit beside fuel burn, emissions, and acoustics.

2.0 Technical Discussion

2.1 Overview

Propulsion 21 is a NASA-funded task with the overall objective to develop technologies that will enable commercial gas turbine engines to reduce fuel burn, produce fewer emissions, and less noise while increasing reliability. The engine entry into service (EIS) date is 2015. The System Study is a work element of the overall Propulsion 21 task. The focus of this system study was to update the assessment completed in Task Order 23 and re-prioritize advanced technologies so that these technologies may be carefully integrated to achieve the best balance of system benefits between dissimilar and contradictory figures of merit.

The work scope defined for this system study includes the following subtasks:

1. Define engine and aircraft technology baselines
2. Update Technology Impact Matrix (TIM) and Technology Audit Datasheets (TAD) of proposed technologies
3. Define Response Surface Equation (RSE) and perform One-On technology ranking
4. Perform Engine System-Level Impact
5. Identify Modeling Shortfalls and Make Recommendations for Future Efforts

Four technologies, included in NAS3-01135 Task Order 37, were not included in the system study because they did not have a direct effect on engine fuel burn, noise or NOx emissions. These were: disk life meter, adaptive controls, bearing systems and fuel systems. In addition, advanced materials, although previously assessed under NASA program NAS3-98004 Task Order 14, were not part of this task's scope.

2.1.1 Subtask 1 - Define Engine and Aircraft Technology Baselines

The balanced noise EROC 2015 UEET-QAT engine and aircraft was selected and agreed by NASA and GEA for use in the Propulsion 21 system study. This engine was developed as a derivative of the UEET Medium Engine for NASA Contract NAS3-01135 (Task Order #2 - Advanced Fan Propulsion System Design Study) that represents an advanced aircraft and engine system with the best fit for the Propulsion 21 system study. This engine was flown on the UEET-QAT aircraft in a typical mission to determine the fuel burn, acoustics, and emissions.

GEA's balanced noise EROC 2015 UEET-QAT engine concept was designed to revolutionize the state of the art in propulsion technology for the next 15 to 20 years, with the biggest reduction in aircraft fuel burn (CO_2), emissions (NO_X), noise, and Engine Related Operating Cost (EROC) relative to a baseline engine. Multi-functional revolutionary engine technologies were carefully integrated to achieve the best balance between challenging and contradictory program goals with an EIS of 2015.

The 2015 UEET-QAT engine key features include:

- Ultra low noise, low speed, counterrotating swept fan blades with suction side bleed
- Reduced core debris ingestion, counterrotating vaneless booster with no Variable Bleed Valves (VBV).

- Re-circulating booster tip treatment for improved stall margin
- High pressure ratio, 6-stage high-pressure compressor (HPC), all blisk rotors with advanced material in the aft stages
- Ultra low emissions twin annular pre-swirl (TAPS) Mod2+ combustor with ceramic matrix composite (CMC) liners
- Non deteriorating, low leakage aspirating seals
- Two stage HPT with advanced CMC nozzle, next generation blade and rotor materials
- Robust, high DN HP rotor bearings and differential LP rotor bearings
- Simplified main engine frames and architecture
- Counterrotating, vaneless LPT with reduced stages and mini Turbine Rear Frame
- Intelligent Propulsion Controls

GEA provided limited consultation assistance to NASA and universities as they worked at establishing a mutually-agreeable working model of NASA's interpretations of the B777/GE90 and B737/CFM56 engines. It was agreed that it was not necessary for the NASA baseline engines to exactly match the GE90 and CFM56 proprietary engines so that they can remain non-proprietary. Separate meetings were completed with Georgia Tech University and Ohio State University specialists to complete their respective system study.

2.1.2 Subtask 2 - Update Technology Impact Matrix and Technology Audit Datasheets of Proposed Technologies

To assess the impact of the proposed technologies, Technology Audit Datasheets (TAD) were completed for each of the proposed technologies and submitted to NASA program managers for review and concurrence. The benefits and shortcomings are relative to the 2015 UEET-QAT Balanced Noise-EROC baseline engine.

Technology information was extracted from the TAD and summarized on the Technology Impact Matrix (TIM) shown in Table 1, which tabulates all parameters affecting engine design. Control parameter deltas from baseline engine system were generated for each technology. The TIM serves as a listing of the benefits/detriments/enabling relationships each technology is expected to produce. The TIM provides the inputs to modify the engine design for each technology alternative.

There is one emission-related technology, T17 - GEA Intelligent Combustor. This combustion technology targeted to reduce emissions by 50% from the 2015 UEET-QAT baseline.

Technology Impact Matrixes were completed and submitted to the NASA Task manager for concurrence. TIMs were generated for the 2015 UEET-QAT, GE90 and CFM5 engines. Table 1 was completed for the 2015 UEET-QAT baselin engine. It should be noted that technologies T18-20D are for a deteriorated engine case and are therefore a delta from a deteriorated baseline engine.

Listed in the rows are the key control parameter and deltas representing the change relative to the 2015 UEET-QAT baseline for each technology. Shown in the first column are the technology reference number simplified as "T" followed by a number. The second column lists technologies/suite for new engines. T18, T19, and T20 provide different approaches to attain turbine active clearance control. Two approaches use elastic stretch/advanced thermal systems, and the other uses mechanical actuators. Improved, fuel burn for deteriorated engines is evaluated in T18-20D.

GEA provided limited consultation assistance to NASA and universities as they worked at incorporating the proposed Propulsion 21 technologies into NASA's interpretations of the B777/GE90 and B737/CFM56 engines.

2.1.3 Subtask 3 – Response Surface Equations and Perform One-On Technology Ranking

The purpose of the technology ranking sub task was to determine the individual technology that resulted in the greatest benefit to the engine platform. GEA's PREDATER was used to construct the response surface equations (RSE) and conduct the technology assessment for all the new engine technologies. RSE's related technology features to system benefits (fuel burn, acoustics, emission, etc.) constructed under NASA's RASER contract NAS3-01135, Task Order 23 were used on this study because they covered the same parameter range as technologies on this task.

GEA's PREDATER is a linked computer analysis tool that combines parametric engine design with aircraft performance analysis, system cost assessment, airline economic analysis (revenue/cost), and ultimately customer economic value as shown in Figure 4. An engine design model, aircraft performance model, and manufacturing cost model were built and integrated into the PREDATER system. Maintenance cost modeling and airline economic modeling were also incorporated. PREDATER has the capability to also call modules assessing engine manufacturing cost, maintenance cost, and customer value analysis, although for this study, they were not used. The full system was run and checked out to ensure proper communication between the modules.

PREDATER has Design of Experiments (DOE) capability, which allows the rapid investigation of wide design space. The factors that varied in the DOE study are key control parameters, and they are component performance and architecture characteristics. In general, key component characteristics assessed included, but were not limited to, compressor pressure ratio, overall pressure ratio, fan

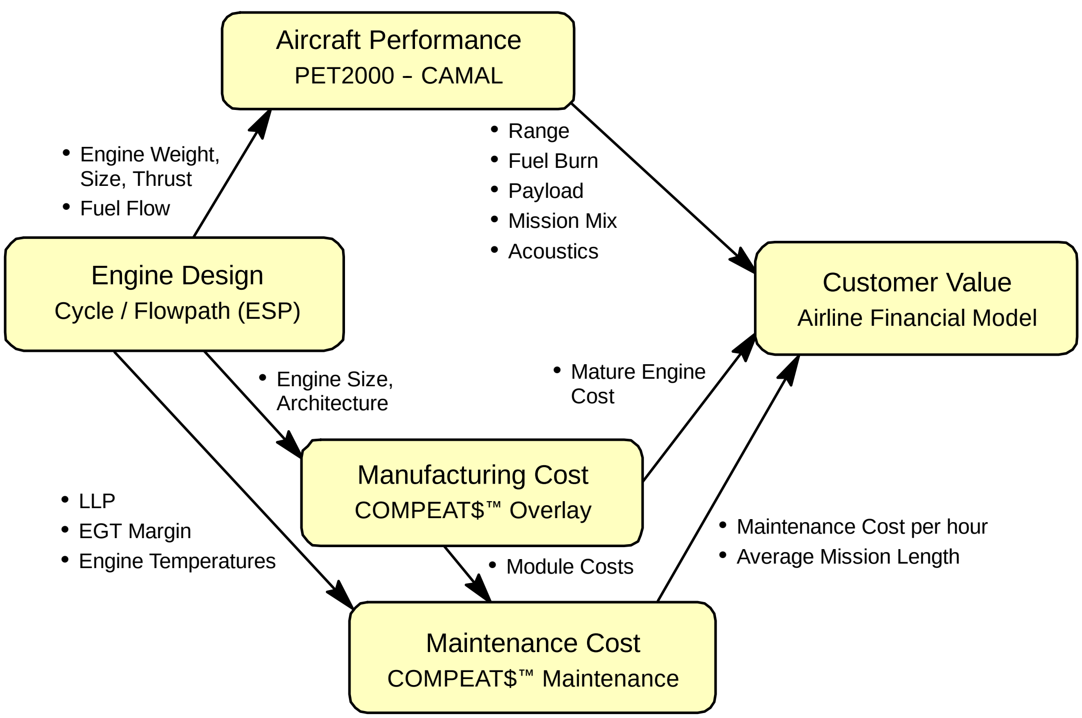

Figure 4. PREDATER Engine Design Evaluation Process

pressure ratio, T41, T3, all HPT and LPT chargeable and non–chargeable flows, all component (Fan, HPC, LPC, HPT, LPT) efficiencies, customer bleed, power extraction, weight, and more. In summary, PREDATER covers the spectrum required for technology evaluation focused on system benefits.

Before doing the full–scale DOE and constructing the response surface equations, the system and methodology were validated. The purpose was to validate the tool and the accuracy of the RSE. Details of the validation were reported in NASA RASER contract NAS3–01135, Task Order 23, Work Element 4.1 – System Study.

PREDATER was used to construct the response surface equations, and the Georgia Tech Technology Impact Evaluation System (TIES) was used to conduct the technology assessment for all the new engine technologies. TIES is a disciplined methodology that combines expert technology impact assessment with a physics–based description of the engine design space. The TIES method was developed by Georgia Tech and was used in cooperation as part of a larger Industry–University partnership that GEA has with Georgia Tech.

The deteriorated engine technologies T18–20D were not included in the TIES One–On study because they were not applied to new engines while the rest of the technologies were. Instead, the results from PREDATER for T18–20D were directly used and they are plotted with the rest of new engine technologies.

2.1.3.1 Fuel Burn, Noise, and NOx Emissions Ranking

One–On technology ranking was completed using the baseline 2015 UEET–QAT Balanced Noise–EROC engine configuration from Task Order 23. A single technology was inserted in the model to assess the system impact. After that system impact was determined, the evaluated technology was removed and the next one to be evaluated was inserted. The aircraft configuration remained fixed for each technology One–On evaluation, but adjusted for installation effects (engine weight, pylon ripple, and drag). Throughout the study, fuel burn refers to fuel burned on a 5600 nautical mile (nm) mission. All technology evaluation charts show delta percent values from baseline, except the NOx emissions chart that is with respect to 1996 ICAO standard.

Figure 1 shows the results for fuel burn impact for all the specified technologies. The only technology that did not lend itself to being evaluated properly was the Long Duct Mixed Flow nacelle (T4). This technology required a complete redesign of the engine cycle to take full advantage of the technology. In addition, technologies T18–20D were for a deteriorated engine case and as such were delta to a baseline deteriorated engine.

Figure 2 shows the assessment for the acoustic technologies. Notice that the Long Duct Chevron Mixer (T4) was not assessed, although it should provide significant benefit in terms of noise. The 2015 UEET–QAT engine is a short duct, separated flow design and the Long Duct Chevron Mixer nacelle, although included here for reference, will require a complete baseline engine redesign. This was beyond the scope of this study.

Figure 3 shows the NOx emissions benefit with respect to the 1996 ICAO standard. The advanced TAPS single annular combustor (SAC) mixer was projected to deliver this emissions level. The predicted LTO NOx data for T17 (GEA intelligent combustor) reflected the potential benefit of the TAPS design to meet the program goal of reducing NOx by 50% from baseline 2015 UEET–QAT level, equivalent to 15% additional reduction from 1996 ICAO limit (the QAT baseline is 70% below 1996 ICAO limit while Propulsion 21 is 85% below 1996 ICAO limit).

GE–Aviation provided consultation assistance to NASA, Ohio State University and Georgia Institute of Technology specialists regarding how to model the technologies on NASA's interpretations of the B777/GE90 and B737/CFM56 engines and deterioration model development.

2.1.4 Subtask 4 – Perform Engine System Level Impact

Technologies evaluated during Subtask 3 were combined and, when feasible, incorporated into a new Intelligent Engine All–Technology configuration. An engine–level assessment of the overall benefits to the system was completed as a function of fuel burn, noise, and emissions (NOx).

The engine system–level impact was estimated by selecting the best technologies, among the incompatible technologies, and including all the beneficial technologies.

Table 3 shows the technologies combined to obtain the cumulative fuel burn and noise improvements at the engine level. The engine system level impact was estimated by the optimal combination of technologies, resulting in potential 1.89 EPNdB cumulative noise margin improvements, 1.34% fuel burn reduction, and 50% NOx emissions reduction from the 2015 UEET–QAT baseline engine.

GE Aviation provided support to the universities as they expanded and validated improved analysis capabilities. One of these areas was the turbine exhaust gas temperature (EGT) trending algorithm.

2.1.4.1 EGT Trending Algorithm

Data recorded from on–wing commercial engines was given to Ohio State University (OSU) to aid them in their system study of engine deterioration. The data was also examined internally to aid OSU's comprehension. As a consequence of the internal review, it was decided to assess the quality of the data to "self–check" the value of measured EGT using other recorded parameters.

An algorithm was developed using the measured aircraft altitude, Mach number, inlet total temperature, rotor speeds, and fuel flow to the measured EGT. In addition, the data "self–checking" could also provide some insight into an engine's deterioration in service, as the divergence of the measured and synthesized values increases over time.

Several sets of data from in service engines were examined using the algorithm coded in MATLAB. The accuracy of the EGT model was characterized by calculating the standard deviations of the differences between the measured and synthesized values over the whole service history and for values when the engine was newly installed (<500 cycles).

There was a considerable amount of "noise" (random instrumentation error) in the recorded data, so to perceive any general trend the results were smoothed out against time. The data samples evaluated for this exercise were divided into 100 and 1000 point group samples. The 1000 point samples were used to characterize a macro trend in the data, and the 100 point groups a micro trend. Combined, the groups were used to establish a smoothed representation of the overall EGT history.

This example served to demonstrate the handling of the engine data, allowing some model calibrations to be performed, and served to prompt some new ideas in ways to address the complex phenomena involved.

2.1.5 Subtask 5 – Identify Modeling Shortfalls and Make Recommendations for Future Efforts

The only technology that did not lend itself to be properly evaluated was the Long Duct Mixed Flow Nacelle (T4). This technology requires a complete redesign of the engine cycle to take full advantage of its benefits. However, it was not recommended at the time to pursue this type of engine configuration since prior studies at GE–Aviation have shown that airline customers are not receptive to the maintainability drawbacks of this configuration.

Recommendations for future work include, but are not limited to:

- Development of customer value analysis as a figure of merit
- Validation of university–developed engine deterioration model.

3.0 Conclusions

The following tasks were accomplished within the original work scope:

- Reached agreement with NASA and Universities regarding work scope and baseline engine/aircraft definition
- Completed task plan
- Built the system model using the 2015 UEET–QAT as baseline engine and aircraft
- Completed TAD and TIM of selected technologies for 2015 UEET–QAT Balance Noise–EROC, and NASA's interpretation of GE90, and CFM56 engines
- Completed One–On technology ranking for proposed technologies on the 2015 UEET–QAT Balance Noise–EROC engine
- Completed engine system impact for 2015 UEET–QAT Balance Noise–EROC engine
- Identified shortfalls and/or issues with modeling Propulsion 21 technologies and proposed recommendations
- Presented final oral presentation
- Completed final written reports (proprietary and non proprietary versions)
- Provided consultation to Ohio State University specialists on how to assess provided engine deterioration data and validate new analytical model under development
- Provided consultation to Georgia Tech specialists regarding modeling of technologies in baseline engines and reviewed the final report

Evaluated each technology for the Intelligent Engine System (Propulsion 21) system study to determine the impact to fuel burn, acoustics, and NOx emissions.

The top six fuel burn technology rankings for a new engine are:

1. T18 (cooled cooling air used for ACC)
2. T19 (LPT nozzle cooling air used for ACC)
3. T7 (intelligent HPT rotor cooled cooling air system)
4. T11 (advanced HPT stage 1 blade)
5. T20 (mechanical actuators)
6. T15 (HPT endwall contouring)

Among the acoustic technologies T5 (Plasma actuators), T6 (vortex jet stabilizer), T1 (synthetic jet fluidic injection), and T2 (shape memory alloy fan chevron nozzle) had the highest acoustic benefits. Regarding all acoustic technologies, only T3 (active liners) had a beneficial fuel burn advantage.

Among the emission technologies, T17 (GEA intelligent combustor) reduced NOx by 50% from the baseline 2015 UEET–QAT engine level, equivalent to 15% additional reduction from 1996 ICAO limit.

The optimum combination of technologies and their overall benefits to the system resulted in potential improvements of 1.89 EPNdB cumulative margin, -1.34% fuel burn, and 50% NOx reduction from the 2015 UEET-QAT baseline. All the technology evaluations, except T18-20D, were based on new engines where the engine was resized to obtain the maximum system benefit while maintaining the same cycle parameters as the 2015 UEET-QAT baseline. The impact of turbine clearance control on deteriorated engines, T18-20D, was also evaluated.

The developed EGT trending algorithm cannot be viewed as a successor or substitute for the types of analysis that are currently performed by various commercial engine tracking and trending operations. The primary purpose of the exercise was to demonstrate how a credible engine EGT signature could be synthesized from the relatively sparse and noisy sets of data available from turbofans in airline service, and how the data could be used to characterize engine deterioration in a more simple manner.

4.0 Schedule and Expenditure Summary

Figure 5 shows the work element detailed schedule.

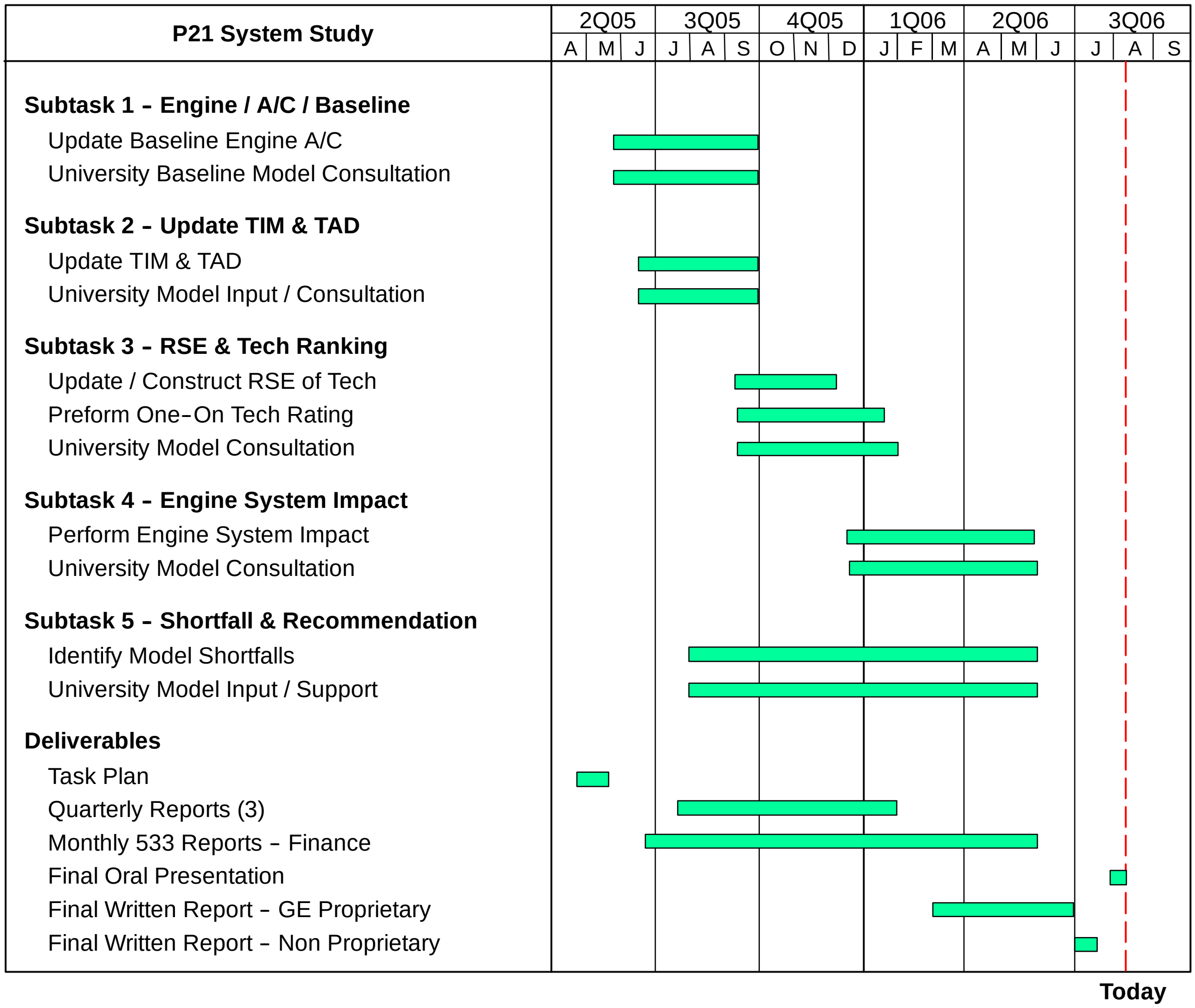

Figure 5. System Study Schedule

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Responsible person, organization code RB, e-mail: Clayton.L.Meyers@nasa.gov, 216-433-3882.

14. ABSTRACT
For the Intelligent Engine System (Propulsion 21) study, each technology was evaluated to determine the impact to fuel burn, acoustics, and NOx emissions. The optimum combination of technologies and their overall benefits to the system were also evaluated, resulting in noise improvement potential of 1.89 EPNdB cumulative margin,-1.34 percent fuel burn, and 50 percent NOx reduction from the 2015 UEET-QAT baseline. All the technology evaluations, except T18-20D, were based on newengines, where the engine was resized to obtain the maximum system benefit while maintaining the same cycle parameters as the 2015 UEET-QAT baseline. The impact of turbine clearance control on deteriorated engines, T18-20D, was also evaluated. Recommendations for future system study work include, but were not limited to, validation of a university-developed engine deterioration model and customer value analysis as figures of merit beside fuel burn, emissions, and acoustics.

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